

TITLE

Method of Producing Powder Metal Parts From  
Metallurgical Powders Including Sponge Iron

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INVENTORS

John C. Kosco  
Keith E. Newman

10 CROSS REFERENCE TO RELATED APPLICATIONS

Not applicable.

STATEMENT REGARDING FEDERALLY  
SPONSORED RESEARCH OR DEVELOPMENT

15 Not applicable.

TECHNICAL FIELD AND INDUSTRIAL  
APPLICABILITY OF THE INVENTION

20 The present invention is directed to a method of producing material and parts from metallurgical powders, and is more particularly directed to a method of producing material and parts from metallurgical powders that include at least a portion of sponge iron. The method generally includes compressing at least a portion of a metallurgical powder to form a green compact, and  
25 subsequently sintering the green compact to provide a sintered compact. The sintered compact optionally is further processed, such as by hot forming, to densify and/or adjust the dimensions of the sintered compact. The present invention also is directed to powder metal materials formed by the method of the

invention, as well as to articles of manufacture fabricated from the materials. The method of the present invention is considered particularly advantageous in the fabrication of bearings, cams, gears, and sprockets, but also may be applied in the fabrication of other parts, including structural parts.

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#### DESCRIPTION OF THE INVENTION BACKGROUND

The following conventional process is used to form parts from a metallurgical powder. One or more metal or metal-containing powders satisfying applicable process constraints and meeting requirements of the desired end product are selected. An internal lubricant is included with the metallurgical powders, and a homogenous blend of the one or more metallurgical powders and the internal lubricant is prepared. As used herein, a "metallurgical powder" refers to a homogenous blend of particulate materials that includes one or more metal or metal-containing powders, whether alloyed or unalloyed powders, and that also may include one or more internal lubricants and other additives as are known in the powder metallurgy art. As used herein, an "internal lubricant" is a lubricant that is present substantially homogenously throughout a metallurgical powder. An internal lubricant may be contrasted with an external lubricant, which is applied either to the external surface of a powder metal compact or to the surface of a molding die in which a powder metal compact is molded.

All or a portion of the lubricant-containing metallurgical powder blend is placed in a molding die and pressed into a green compact of a desired shape. The green compact is shaped so that a powder metal part having the desired

shape and dimensions results after further processing of the green compact.

The green compact is then sintered, typically at a temperature in the range of 1900-2400°F (1066-1316°C) for iron-base compacts, in an electric or gas-fired belt, pusher, or batch sintering furnace to consolidate the powder particles and

- 5 increase the density of the compact. The internal lubricant is removed during the sintering step. Thus, the sintering step must occur at a temperature above the melting temperature of the internal lubricant.

It is known to use a hot forming or forging step following a conventional sintering step to densify and adjust the dimensions of the compact to more

- 10 closely approach the dimensions of the desired part. To prepare the sintered compact for hot forming or forging, the compact is first reheated, typically to a temperature in the range of about 1400°F to about 2100°F (about 760°C to about 1150°C). The reheating step may be carried out by induction heating the already sintered compact. This is typically done by passing the compact through the
- 15 interior of a helically arranged metal induction work coil carrying an alternating current. The alternating current creates a varying magnetic field around the coil, and the magnetic field heats the compact by inducing electrical resistance and hysteresis losses in the compact. Once the compact has been reheated, it may then be hot formed or forged, typically at 40-70 tons/in.<sup>2</sup> ("tsi"), in a heated die
- 20 that is slightly larger than the die used to form the original green compact. The heated die is at a temperature less than that of the reheated compact, and typically is maintained at, for example, a temperature within the range of 400°F to 800°F (204°C to 427°C) for iron-base compacts.

In the case of iron-base compacts, for example, the conventional sintered and hot formed or forged compact typically has a density in the range of 7.6-7.85 g/cc, which is 97-99.8% of theoretical full density. As used herein, an "iron-base" compact is a compact including greater than 50 weight percent iron,

5 whether in elemental or alloyed form.

In conventional powder metallurgy techniques, internal lubricants are employed as a means of facilitating removal of the green compact from the die and to aid in particle rearrangement during compaction. In the absence of an internal lubricant, at the molding pressures typically used to form green

10 compacts, the compacts may adhere to the surface of the die, which may result in galling of the die surface after only a very small number of compacts have been formed in the die. Consequently, the die wears quickly and has to be replaced on a frequent basis, resulting in substantial expense. Lubricants, while alleviating the problems of adherence and die damage, are problematic in a  
15 number of ways. For example, the cost of the lubricants increases the cost of the finished parts. The lubricants also must be substantially removed from compacts during processing, and the evolution of the decomposition products of lubricants from compacts during sintering may raise environmental concerns. Thus, eliminating internal lubricants would be of great value.

20 It also would be advantageous to be able to reduce the molding pressures at which green compacts are formed so as to lessen wear on the dies. It is generally believed, however, that molding iron base metallurgical powders at pressures less than 20 tsi will not result in a compact having sufficient green

strength. Green strength refers to the ability of a green compact to maintain its size and shape during handling and storage prior to sintering. Low green compact densities may be raised in subsequent sintering and working operations, but a green strength less than about 1,000 lbs/in.<sup>2</sup> (psi) is considered unacceptable because the compacts may easily crumble or fracture when handled.

As noted, the internal lubricant must be substantially removed from the powder metal compacts during processing. Failure to remove the internal lubricant reduces the maximum part density that may be achieved and otherwise

compromises the properties of the finished part. For example, corrosion resistance of stainless powder metals may be degraded if all internal lubricant is not removed.

Conventional electric or gas-fired belt sintering of iron-base powder metal compacts typically subjects the compacts to high temperatures for about 20 to 60 minutes, allowing the internal lubricant to gas off. Electric and gas-fired sintering furnaces are relatively inefficient heating devices and require large energy expenditures. Thus, the length of the sintering step required to process each compact involves substantial energy consumption and cost, and the sintering step constitutes a significant portion of the overall processing time and expense necessary to produce powder metal parts. In addition, belt, pusher, or batch sintering furnaces are large and expensive machines, requiring significant capital expense and a large floor space in the plant. Thus, in addition to the

elimination of internal lubricant, it also would be advantageous to form powder metal parts without the need for conventional belt, pusher, or batch sintering.

Prior efforts to eliminate the use internal of lubricants in the fabrication of powder metal parts have met with only moderate success. One approach, 5 seen in United States Patent No. 5,682,591 issued to Inculet ("the '591 patent"), has been to use an electrostatic process to charge lubricant particles that are then sprayed onto the die surface prior to each molding cycle. It is intended that lubricant on the die surface would prevent adhesion of the compact and inhibit die wear. The entire disclosure of the '591 patent is hereby incorporated herein 10 by reference. Success with the process of the '591 patent, however, has been limited because coverage of the die surface by the lubricant spray can be inconsistent if improperly sprayed. At the high molding pressures conventionally used to form green compacts, even one mis-spray can produce die damage. Molding dies could better withstand insufficient die coverage resulting from mis- 15 sprays if lower molding pressures could be used. However, lower pressures result in compacts with lower green strength and lower densities.

Accordingly, it would be advantageous to provide a method of forming powder metal parts wherein little or no internal lubricant must be included in the metallurgical powder. It also would be advantageous to allow for the use of 20 reduced molding pressures so as to reduce die wear. It would additionally be advantageous to avoid the necessity for the use of conventional belt, pusher, or batch sintering techniques in order to reduce time and expense associated with those processes

## SUMMARY OF THE INVENTION

The present invention addresses the above-described needs by providing a method of forming a powder metal material from an iron-containing metallurgical powder including at least a portion of sponge iron. At least a portion of the metallurgical powder is compressed to provide a green compact. The green compact is subsequently sintered to provide a sintered compact. The sintered compact may be further processed, if desired, such as by hot forming the sintered compact, to adjust at least one of the density and dimensions of the compact.

The metallurgical powder used in the method of the present invention may include its entire iron content in the form of sponge iron. High levels of sponge iron will be especially suitable when parts made by the method of the present invention are to be used in low strength applications where high ductility is required. When the parts are to be applied in heavy-duty structural applications, the amount of sponge iron in the metallurgical powder preferably is about 10 up to about 50 weight percent, and more preferably is about 15 up to about 25 weight percent, based on the total weight of the metallurgical powder.

The sponge iron may be in the form of, for example, one or more pure sponge irons (which may include incidental impurities) and/or one or more sponge irons produced from alloyed steel. In addition to including pure and/or alloyed sponge irons, the metallurgical powder may include, for example, at least one of a pure atomized iron powder and an atomized iron-containing powder.

The present inventor has discovered that when the metallurgical powder used in the method of the present invention has iron content present entirely or substantially as sponge iron (and lacks any substantial fraction of atomized iron and iron-containing powders), molding pressures of less than

5 about 20 tsi may be used to form green compacts having green strength of at least 1000 psi (as determined by, for example, test method MPIF Standard No. 15 (ASTM B312, ISO 3995)). Such molding pressures are substantially lower than pressures conventionally used to form iron-base green compacts and would produce significantly less die wear. Therefore, although higher molding

10 pressures may be used in the present method, it is preferred that molding pressures less than about 20 tsi be used when the metallurgical powder includes an iron content composed entirely or substantially of sponge iron and lacks any substantial fraction of atomized iron or iron-containing powders. When the low molding pressures are used with the present method, it is possible to

15 successfully form green compacts from powders including little or no internal lubricant with the occurrence of substantially less die wear than would be encountered with higher molding pressures. Thus, although the metallurgical powder may include an internal lubricant, it preferably includes such lubricant in amounts no greater than about 0.3 weight percent, based on the weight of the

20 powder.

The amount of sponge iron included in a particular metallurgical powder processed by the method of the present invention may be dictated by a trade-off between green strength and the resultant properties, particularly

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hardness, strength, and/or impact strength, of the final sintered part. As the sponge iron content of the metallurgical powder increases, green strength will increase at any given molding pressure. Conversely, as the powder's sponge iron content increases, it is possible to mold the powder at increasingly lower pressures and still obtain compacts having acceptable green strength to allow the compacts to be handled. Increasing the sponge iron content, however, can adversely affect sintered properties. If the sponge iron in the powder is in un-alloyed form, it dilutes the total alloy content of any atomized alloy/sponge composite and will, therefore, decrease hardenability. This may lower strength and hardness values, while increasing elongation. One of ordinary skill may, without undue effort, determine suitable contents of sponge and atomized iron and iron-containing powders for parts used in particular applications. In general, if the sponge iron content of the metallurgical powder is less than about 10 weight percent, little increase in green strength will typically result. If, on the other hand, the sponge iron content exceeds about 40 weight percent, in general, strength and hardness will decrease to levels unsuitable for structural applications, although unacceptable decreases may not be observed if the powder includes a pre-alloyed sponge iron powder.

With the exception of the unique initial molding pressures that may be used in the process of the present invention, processing of the metallurgical powder may be conducted using techniques known in powder metallurgy. Thus, for example, the green compacts formed by the method of the present invention may be sintered in an electric or gas-fired batch, belt, or pusher sintering furnace.

In one form, the method of the present includes sintering the green compact by induction heating. The use of induction sintering of green compacts formed from metallurgical powders, which may include an amount of sponge iron,

is an invention disclosed in detail in a co-pending United States patent

5 application Serial No. \_\_\_\_\_, which is entitled "Method of Forming Powder

Metal Parts" and is filed on even date herewith (hereinafter referred to as the "co-pending application"). The entire disclosure of that co-pending application is incorporated by reference herein. Induction sintering is facilitated by the method of the present invention because the metallurgical powders may lack or be

10 substantially free of internal lubricants. Induction sintering requires substantially less time and energy consumption relative to conventional sintering using an electric or gas-fired batch, pusher, or belt sintering furnace

The present invention also is directed to powder metal materials produced by the method of the present invention, and to articles of manufacture, 15 such as powder metal bearings and structural parts, including powder metal materials produced by the present method.

The reader will appreciate the foregoing details and advantages of the present invention, as well as others, upon considering the following detailed description of embodiments of the invention. The reader also may comprehend 20 additional details and advantages of the present invention upon practicing the method of the invention or upon using the powder metal parts and articles produced by a process including the present method.

## DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

As discussed above, internal lubricants included in metallurgical powders are conventionally removed by sintering parts molded from the metallurgical powders in a belt, pusher, or batch sintering furnace. It would be advantageous to eliminate the lubricant removal step from the process. As disclosed in the co-pending application, inductive heating can be used to successfully sinter compacts of metallurgical powder if the internal lubricant content of the compacts is no greater than about 0.3 weight percent. For comparison, the typical internal lubricant content of conventional iron-base metallurgical powders ranges from about 0.5 to about 1.3 weight percent. The sintered compacts may then be densified and dimensionally adjusted in a hot forming or forging die in a subsequent step, if desired. Because inductive heating heats compacts to sintering temperature quickly, inductive sintering will require substantially less time, and also less expense, than conventional sintering such as electric or gas-fired belt, pusher, or batch sintering. Self-lubricating dies, for example, may be used to form the green compacts from metallurgical powders including not more than 0.3 weight percent internal lubricant so as to prevent adhesion to the die surface and unacceptable die wear.

When conventional powder compaction processes are utilized to form fully dense compacts, the compacts are typically sintered in a conventional electric or gas-fired belt, pusher, or batch furnace. The furnace heats the parts by conventional processes (*i.e.*, conductive, convective, and radiative processes)

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at a sufficiently slow rate to permit the escape of gaseous byproducts from the decomposition of internal lubricants. However, as disclosed in the incorporated co-pending application, the effective heating of green compacts from metallurgical powders by induction requires that the compact contain no more than about 0.3 weight percent of internal lubricant. Internal lubricant levels greater than about 0.3 weight percent affect the induction sintering process in two distinct manners. First, the excessive internal lubricant inhibits effective thermal and electrical coupling of the individual powder particles under the action of an induction coil. The second factor complicating induction heating of green compacts is the observation that the byproducts of internal lubricant decomposition evolve more rapidly than in conventional sintering. If excessive, these gases are unable to be liberated from deep within the part quickly enough to eliminate the risk of part fracture from large internal stresses generated by the entrapped gases.

When conventional hot forming or forging is used in the production process, compacts are typically coated with a graphite slurry before being heated in an induction coil to sub-sintering temperatures just prior to being placed in the hot forming or forging die. The carbon in the graphite slurry will diffuse into the compact and undesirably harden the compact's surface unless the induction heating is done very quickly. Thus, as explained in the incorporated co-pending application, it is believed that one could not effectively remove internal lubricant by heating a compact including greater than about 0.3 weight percent of internal

lubricant for a prolonged period in the induction heating step that occurs just prior to hot forming or forging.

The present inventor has discovered that the ability to form a green compact having suitable green strength (at least 1000 psi) is greatly facilitated by

5 including at least a portion of sponge iron in the metallurgical powder. Sponge iron exhibits only modest compressibility, achieving typical densities of 5.0-6.6 g/cc when compressed at conventional compaction pressures. However, the inventor has observed that green compacts of sponge iron powder possess outstanding green strength. As is well known in the powder metallurgy field,

10 sponge iron is a coherent, porous mass of substantially pure iron produced by solid-state reduction of iron oxide, typically by hydrogen or carbon, and, as its name suggests, is sponge-like in appearance. Typically, sponge irons exhibit apparent densities of 2.3-2.65 g/cc. Commercial sponge irons normally include 96.5 weight percent iron minimum and 0.4-0.65 weight percent manganese, and

15 exhibit 0.2-1.2 weight percent hydrogen loss. Hydrogen loss is a measure of the weight loss of a powder when sintered in pure hydrogen at specified test conditions. The measurement and significance of hydrogen loss is known to those having ordinary skill in the powder metallurgy arts. Sponge irons are most commonly used in bearing applications, and producers in the U.S. include Pyron

20 (Niagara Falls, N.Y.), North American Hoganas (Allentown, Pa.), and Hoeganaes (Riverton, N.J.).

As described herein and in the incorporated co-pending application, green compacts including sponge iron and having green strengths in excess of

1000 psi were formed using compaction pressures as low as 5-15 tsi, pressures substantially lower than those conventionally used to form green compacts.

Mixes of sponge iron powders and atomized powders may be desirable because atomized powders are generally more compressible than sponge iron and can be

- 5      pressed at 30-50 tsi into green compacts having densities of about 6.65-7.25 g/cc. Thus, the addition of sponge iron to a metallurgical powder will permit the molding of green parts having acceptable green strength at lower molding pressures than powders lacking sponge iron, and this may permit the use of little or no internal lubricant in the metallurgical powder.

10       The present inventor has formed green compacts including sponge iron and having suitable green strength at pressures less than 20 tsi, which is below the conventional pressure range used to mold green compacts of iron base atomized metallurgical powder. The inventor has found that because the metallurgical powders used in the method of the present invention may be

15      molded at reduced pressures, the internal lubricant content of the powders may

be reduced or eliminated without the occurrence of unacceptable die wear.

Because, as described above, the presence of internal lubricants in metallurgical powders creates a number of problems, the metallurgical powders used in the method of the present invention preferably lack or include no more than about

20      0.3 weight percent internal lubricant.

In addition to sponge iron, the metallurgical powders used in the method of the present invention may include one or more additional metal-containing powders. As used herein, "metal-containing" powders is to be

interpreted in a broad sense, and include metals alloyed with metals and/or other elements, mixed powders including metals, and pure metal powders (such as pure iron powder). All powder components may include incidental impurities. If compacts formed from the powders are to be induction sintered (as disclosed in 5 the co-pending application), then the powders must include a metallic material capable of being heated through the action of alternating electric fields. That condition may be satisfied, for example, by the presence of a suitable content of sponge iron alone.

In a preferred form, the metallurgical powder includes one or more of a 10 pure atomized iron powder and atomized alloyed iron powder, in addition to sponge iron powder. More preferably, the metallurgical powder is composed predominantly of sponge and atomized iron in elemental and/or other forms. The inclusion of one or more sponge iron and/or iron-containing powders in the metallurgical powder will reduce the minimum molding pressure required to form 15 a green compact having green strength of at least 1000 psi, and metallurgical powders having iron content entirely or substantially in the form of sponge iron may be molded to acceptable green strength at molding pressures less than about 20 tsi.

One possible embodiment of the metallurgical powder includes the 20 following elemental composition, which is provided by preparing an appropriate blend of particulate materials: 0 up to about 3 weight percent graphite; 0 up to about 12 weight percent nickel; 0 up to about 3 weight percent molybdenum; 0 up to about 10 weight percent copper; 0 up to about 2 weight percent

manganese; 0 up to about 20 weight percent chromium; 0 up to 0.3 weight percent internal lubricant; and iron and incidental impurities. A more preferred form of the metallurgical powder has the following composition: 0 up to about 1 weight percent graphite; 0 up to about 6 weight percent nickel; 0 up to about 2 5 weight percent molybdenum; 0 up to about 3 weight percent copper; 0 up to about 1 weight percent manganese; 0 up to about 3 weight percent chromium; 0 up to 0.3 weight percent internal lubricant; and iron and incidental impurities.

While atomized powders exhibit lower green strengths than sponge irons when pressed to green compacts at the same pressures, compacts of 10 atomized powders typically possess excellent sintered properties. Thus, powder metal structural parts can be made from metallurgical powder including primarily atomized powders, while metallurgical powder composed entirely or predominantly of sponge iron powder is more often used for bearings.

Normally, the mechanical properties obtained with sponge iron are 15 inferior to atomized iron powders because of the porosity inherent in sponge irons. However, a hot forming or forging step may be used to close up a significant amount of the porosity typical of sponge iron compacts. Therefore, hot formed or forged articles of blends of atomized iron or iron alloys and sponge iron, or of pure sponge iron, along with elemental additions, can yield properties 20 comparable to sintered compacts of pure atomized powders.

It is preferred that the metallurgical powder be free of internal lubricant. If present, however, it is preferred that the internal lubricant content be limited to no more than about 0.3 weight percent. In that way, the cost associated with

providing internal lubricant may be wholly or substantially avoided. Internal lubricant is typically in the form of a wax or stearamide compound, but any lubricant commonly used in the powder metallurgy art may be used, including, but not limited to, ethylene bis-stearamide, zinc stearate, and stearic acid.

- 5 Reducing or eliminating the internal lubricant content will be facilitated by increasing the fraction of sponge iron in the metallurgical powder to thereby allow molding at lower molding pressures and a reduced possibility of die damage.

At least a portion of a metallurgical powder including sponge iron is compacted in a die under pressure sufficient to form a green compact. In one embodiment, the metallurgical powder is compressed at a pressure in the range of 10 up to 70 tsi to form a green compact. The molding pressure preferably is no greater than 20 tsi when the sponge iron content of the metallurgical powder allows satisfactory molding at such low pressures. Preferably, the green compact has green strength of at least 1,000 psi and a density of at least about 15 4.0-4.5 g/cc. The green compact may be formed in a die employing die wall lubrication as is taught in the '591 patent. In addition, the die may be of a type known in the art employing various die cavity coatings to reduce friction and wear during molding. Lubrication of the die wall eliminates or reduces the need for internal lubricant by reducing adhesion of the compact to the die wall and 20 abrasion between the die wall and the compact. Thus, a green compact having sufficient green strength and little or no internal lubricant may be provided from a suitable metallurgical powder using very low molding pressures.

Following compaction, the green compact may then be sintered by conventional techniques. The green compact also may be sintered by induction heating, as is described in the incorporated co-pending application. The sintering temperature typically is, for example, a Fahrenheit temperature of 60-95% of the 5 melting point of the primary component of the compact. Those having ordinary skill in the powder metallurgy art may readily ascertain a suitable sintering temperature and time-at-temperature for a particular green compact.

As explained in the incorporated co-pending application, sintering by induction heating is a significant improvement over prior art powder metal 10 sintering methods. For instance, induction sintering eliminates the need for sintering the compacts using an electric or gas-fired belt, pusher, or batch sintering furnace, so energy costs are reduced and a typical twenty-minute sintering time is eliminated. Induction heating may be carried out by inducing a current in the green compact so as to raise the compact to a suitable sintering 15 temperature, typically in the range of 1600-2500°F (871-1371°C), for a time at temperature sufficient to produce a sintered compact. Alternating current may be passed through the coil to thereby induce a secondary current through electromagnetic induction within the green compact.

Preferably, the sintering time using inductive sintering is in the range of 20 about 2 to about 600 seconds time-at-temperature. For example, an induction sintering time of 20 to 180 seconds may be employed to sinter green compacts used to form a pinion gear, wherein the compacts have a one-inch outer diameter, a length of one inch, and are formed from a metallurgical powder

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including substantially iron powder and, optionally, relatively minor amounts of graphite, nickel, molybdenum, copper, manganese, and chromium, and including sponge iron. It will be understood that the suitable range of sintering times will vary based on part size, geometry, and composition. One of ordinary skill in the  
5 art may readily determine an appropriate induction sintering regimen for any particular powder metal compact using available induction heating equipment.

As noted above, certain embodiments of the method of the present invention may employ a metallurgical powder including little or no internal lubricant. In such cases, there would exist little or no insulating film between the individual  
10 powder particles. As such, thermal coupling between the powder particles is improved to the point that compacts can be induction heated rapidly (usually in less than 60 seconds for iron-base compacts of typical sizes) through their entire mass to sintering temperatures in the range of 1600-2500°F (871-1371°C) using an induction coil.

15 Following sintering, whether by induction heating or other means, the sintered compacts may be further processed using known powder metal processing techniques. For example, the temperature of the sintered compacts may be adjusted to a temperature below the sintering temperature, and then hot formed or forged to densify and adjust dimensions of the compacts. Typically,  
20 the sintered compacts would be either cooled or heated to a temperature in the range of 1400-2100°F, and more typically between 1700-1900°F for iron-base compacts, before being hot formed or forged. Hot forming and forging are carried out in a heated die. Typical die temperatures are in the range of about

200°F up to about 800°F (93°C up to 427°C), and preferably are in the range of about 400°F to about 600°F (204°C to about 316°C). The preferred die

temperature range is believed to minimize hot forming and forging tool wear, better control heat loss from the part, and better control final part dimensions

- 5 after hot forming or forging. Pressures applied to the powder metal part in the hot forming or forging die typically are in the range of about 20 tsi up to about 90 tsi, and preferably the hot forming or forging pressure is about 40 tsi.

One having ordinary skill may, without undue experimentation, readily determine suitable temperatures and pressures for a hot forming process used in 10 the method of the present invention. As an example, a green compact is molded from an iron-base metallurgical powder optionally including up to 3 weight percent graphite, up to 12 weight percent nickel, up to 3 weight percent molybdenum, up to 10 weight percent copper, up to 2 weight percent manganese, up to 20 weight percent chromium, and with at least a portion of the 15 iron being present as a sponge iron powder. Assuming a sintering temperature of about 2500°F (1371°C) for the green compact, the hot forming or forging temperature for the sintered compact may range from a minimum of about 1200°F (1371°C) up to about 2100°F (1149°C), with the preferred hot forming or forging temperature being about 1800°F (982°C).

- 20 The following Table 1 illustrates the advantages that may be gained by including sponge iron in the metallurgical powders used in the method of the present invention. Table 1 lists the green strength (psi) of green compacts formed at various compaction pressures from metallurgical powders including

atomized iron powder, sponge iron powder, or a combination of atomized and sponge iron powders, both with and without internal lubricant. Acrawax™ ethylene bis-stearamide ("EBS") was used as the internal lubricant. Green strength was evaluated by test method MPIF Standard No. 15 (ASTM B312, ISO 5 3995).

Table 1

| Molding Pressure (tsi) | Green Strength (psi) of Compact             |                            |                                            |                                |                                                                          |
|------------------------|---------------------------------------------|----------------------------|--------------------------------------------|--------------------------------|--------------------------------------------------------------------------|
|                        | HP85 with 0.75 weight percent EBS lubricant | HP85 no internal lubricant | R80 with 0.75 weight percent EBS lubricant | R80 with no internal lubricant | 35 weight percent R80 + 65 weight percent HP85 and no internal lubricant |
| 10                     | --                                          | 234                        | --                                         | 1,463                          | 565                                                                      |
| 15                     | --                                          | 605                        | --                                         | 2,794                          | 1,184                                                                    |
| 20                     | 695                                         | 1,146                      | 4,380                                      | --                             | --                                                                       |
| 30                     | 1,311                                       | 2,339                      | 7,042                                      | --                             | --                                                                       |
| 40                     | 1,815                                       | 3,434                      | 9,247                                      | --                             | --                                                                       |
| 50                     | 2,157                                       | --                         | 10,894                                     | --                             | --                                                                       |

R80 is a hydrogen reduced sponge iron powder produced by Pyron. HP85 is an atomized iron alloy powder including 0.85% molybdenum and is 10 available from Hoeganaes. As seen in the table, a suitable green strength (at least 1,000 psi) was not achieved with a metallurgical powder composed of HP85

atomized iron-molybdenum powder and 0.75 weight percent lubricant until 30 tsi of pressure was applied. An acceptable green strength was achieved with HP 85 powder lacking internal lubricant at a molding pressure of 20 tsi, producing a green strength of 1,146 psi. This evidences an advantage to not including an

5 internal lubricant in the powder. As seen from the table, major improvements in green strength are possible by including R80 sponge iron powder in the metallurgical powder mix. For example, a powder including R80 sponge iron powder and EBS internal lubricant molded at 20 tsi had green strength in excess of 4000 psi, while R80 powder without internal lubricant had green strength of

10 1463 psi when molded at only 10 tsi. Thus, the addition of sponge iron permits good green strength at lower molding pressures, and also allows suitable green strengths with lower levels of internal lubricant.

Green compacts of a blend of sponge iron and atomized iron-molybdenum powder had satisfactory green strength (1,184 psi) at 15 tsi. Green

15 compacts of sponge iron may have a density of as little as 4.0 g/cc, and more typically about 5.1-5.4 g/cc, when molded at low pressures. The addition of an atomized powder in the metallurgical powder should result in increased density relative to green compacts formed from sponge iron only. Green compacts including sponge iron only or including both sponge iron and atomized iron or

20 iron alloy powders may be processed according to the present invention as generally described above, but may be molded with satisfactory green strength at lower pressures relative to compacts including only atomized iron powders. As an example, the inventor molded a green compact at 20 tsi from a metallurgical

powder including 97 parts R80 sponge iron powder, 3 parts copper powder, and 0.8 parts powdered graphite. The compact had a green strength of 4400 psi and a density of 5.2 g/cc. The compact was sintered at 2080°F in a N<sub>2</sub>-5%H<sub>2</sub> environment, cooled to 1800°F, and hot formed at 60 tsi. The hot formed part 5 had density of 7.6 g/cc, RC15 hardness, and 100 ksi tensile strength. Thus, the use of sponge iron yielded a handleable part at low pressures with minimal tool wear.

The compact density sufficient to provide green strength of 1000 psi will vary depending on the ingredients in the metallurgical powder. When 10 compacting a powder of 100 weight percent Pyron R80 sponge, a density of 4.0-4.5 g/cc is generally sufficient to obtain a 1000 psi green strength. When compacting a blend of sponge and atomized powders, the density that gives the 1000 psi green strength will vary depending on the sponge weight percentage and the base atomized powder. As an example, a powder blend of 35 weight 15 percent Pyron R80 sponge iron powder and 65 weight percent HP85 powder developed a green strength of 1000 psi at about 13 tsi. A blend of 30 weight percent R80 sponge iron powder and 70 weight percent atomized AISI Series 4600 steel powder reached 1000 psi at about 15 tsi. Those of ordinary skill may, without undue effort, adjust the relative content of individual powders in a given 20 mix to achieve a density when molded at 20 tsi or less that provides suitable green strength.

The ability to produce powder metal compacts having acceptable green strength at low molding pressures (for example, less than 20 tsi) is a

significant improvement over the prior art. This development solves certain compact adhesion and die wear problems encountered in molding compacts with little or no internal lubricant. Substantial or entire elimination of internal lubricant can now be accomplished without significantly compromising the service life of

- 5 the molding die because the lower usable molding pressures eliminate or significantly reduce the occurrence of wear and scoring of and adherence to the die wall. Available die wall self-lubrication systems also may be used with greater confidence as there would be less chance at the lower molding pressures of ruining the tooling if coverage of the die wall with lubricant is incomplete.
- 10 Thus, the useful life of the die may be extended, reducing capital costs. Green compacts produced at the lower molding pressures that may be used in the method of the present invention may be handled without damage and may be induction sintered as generally described herein. The capability to use molding pressures as low as or lower than 10 tsi also allows for the use of smaller
- 15 molding presses, which may be run at a faster rate.

In addition to the available sponge irons listed above, Pyron also produces a family of sponge iron powders, including P-100, D-63, LD-80, R-12, and IC-325 grades. Each has varying particle size distribution, apparent density, and density when compressed at given pressures. North American Hoganas produces SC100, MH80, and NC100 sponge iron powders noted. All of these powders have merit in specific applications, but Pyron R80 powder is favored for use in the present method because of its very high green strength. With regard to atomized powders, major suppliers include Hoeganaes, North American

Hoganas, Quebec Metal Powders (Montreal, Quebec), and Kobelco (Seymour, Ind.). The grades of atomized iron and iron alloy powders shown in Table 2 are examples of those available from these metal powder producers, and all likely may be used in formulations of metallurgical powders that may be processed

5 according to the present invention.

Table 2

| Material Type          | Producer   |                        |                      |                    |
|------------------------|------------|------------------------|----------------------|--------------------|
|                        | Hoeganaes  | North American Hoganas | Quebec Metal Powders | Kobelco            |
| Iron Powder            | 1000 A,B,C | AHC, ASC               | 1001                 | MA300, MA500       |
| Series 4400 Mo Steel   | HP85       | Astaloy 85Mo           | 4401                 | --                 |
| Series 4200 NiMo Steel | 2000       | --                     | 4201                 | 4109 46F2E         |
| Series 4600 NiMo Steel | 4600V      | Astaloy A              | 4601                 | 4600, 4600H, 46F2H |
| Cr Steels              | --         | CrM                    | 4701                 | --                 |

Selection of a particular atomized/sponge powder combination and percentages

10 would depend on desired properties. Thus, for example, if the part were to be used in magnetic applications, pure iron powders might be preferred. If, on the other hand, mechanical properties were of prime concern, then one or more NiMo steel powders might be more suitable.

The following Table 3 lists green strength, density, hardness, and

15 tensile strength properties for several compacts formed by a press-sinter-hot

form sequence from metallurgical powders including iron content in the form of either sponge iron or atomized iron.

Table 3

| Sample | Powder Mixture                            | Process                                   | Green Strength (psi) at 20 tsi | Density (g/cc) | Hardness (Rockwell C) | Tensile Strength (ksi) |
|--------|-------------------------------------------|-------------------------------------------|--------------------------------|----------------|-----------------------|------------------------|
| 1      | Atomized Fe, 2% Cu, 0.8% C                | As Hot Formed                             | 627                            | 7.51           | C19                   | 117                    |
| 2      | Pyron 100 Sponge Fe, 3% Cu, 0.6% graphite | As Hot Formed                             | 1082                           | 7.65           | C22                   | 115                    |
| 3      | R80 Sponge Fe, 3% Cu, 0.6% graphite       | As Hot Formed                             | 4380                           | 7.59           | C15                   | 100                    |
| 4      | Atomized Fe, 2% Cu, 0.8% graphite         | Hot Form, Quench, Temper at 500°F (260°C) | 627                            | 7.51           | C44                   | 117                    |
| 5      | Pyron 100 Sponge Fe, 3% Cu, 0.6% graphite | Hot Form Quench, Temper at 500°F (260°C)  | 1082                           | 7.65           | C38                   | 94                     |
| 6      | R80 Sponge Fe, 3% Cu, 0.6% graphite       | Hot Form, Quench, Temper at 500°F (260°C) | 4380                           | 7.59           | C31                   | 85                     |

- 5        The data of Table 3 confirms that satisfactory green strengths may be achieved at molding pressures of 20 tsi of compaction pressure in all samples including sponge iron. Samples 2, 3, 5 and 6 included either Pyron 100 or R80 sponge iron and had green strengths well in excess of 1000 psi when molded at 20 tsi. Pyron 100 is a hydrogen reduced sponge iron powder, and Pyron 100

and Pyron R80 powders differ primarily in apparent density, flow, and particle size as shown in the following Table 4.

Table 4

| Powder    | Apparent density (g/cc) | Hall Flow (sec/50g) | Screen Mesh Analysis |        |       |       |       |       |
|-----------|-------------------------|---------------------|----------------------|--------|-------|-------|-------|-------|
|           |                         |                     | +80                  | +100   | +150  | +200  | +325  | -325  |
| Pyron 100 | 2.3-2.5                 | 27-35               | Trace                | 2 max. | 10-15 | 15-25 | 25-40 | 28-45 |
| Pyron R80 | 1.0-1.5                 | Poor                | 2 max.               | 1-12   | 15-30 | 15-30 | 20-40 | 15-35 |

5

The highest green strength in Table 3, 4380 psi, was seen in Samples 3 and 6, which contained R80 sponge iron. The green strength of the compacts formed from atomized iron, samples 1 and 4, had unacceptable green strength of 627  
10 psi. The lower molding pressures required to form satisfactory compacts from the powders of samples 2, 3, 5, and 6 should allow for the complete or substantial elimination of internal lubricant without the risk of significant die wear.

Density, hardness, and tensile strength were evaluated subsequent to hot forming and, if applicable, the quench and temper treatment. The densities  
15 of the samples in Table 3 including atomized iron powder, samples 1 and 4, each 7.51 g/cc, were lower than densities of hot formed samples containing sponge iron. That result was somewhat surprising, as it was expected that the hot formed atomized iron parts would exhibit less porosity than parts formed of sponge irons.

The data in Table 3 indicates that very favorable properties can be achieved in hot formed parts containing sponge iron. Although the hardnesses and strengths of parts made with sponge iron are slightly lower than those for parts made with pure atomized powders, these differences are more than

- 5 compensated for by enhanced green strength and the ability to eliminate internal lubricant during formation.

As noted above, the metallurgical powder used in the method of the present invention may include one or more atomized iron and/or iron alloy

powders. The weight percentage of sponge iron that must be present in a

- 10 metallurgical powder to provide a compact with a green strength greater than 1000 psi at a given molding pressure will vary depending on the type and grade of any atomized powders in the metallurgical powder. The following Table 5 shows the dependence of green strength on relative contents of sponge and atomized powders. The table also includes baseline figures for compacts formed  
15 using either 0 weight percent sponge iron or 100 weight percent of two sponge iron types. MH-100 powder is a sponge iron powder available from Hoeganaes having apparent density of 2.55 g/cc and a typical analysis, in weight percentages, of 0.20 SiO<sub>2</sub>, 0.01 C, 0.009 S, 0.01 P, and 0.21 hydrogen loss.

Table 5

| Atomized Powder Type | Sponge Iron Powder Type | Weight Percentage Sponge Iron | Green Strength at Various Molding Pressures (tsi) |      |      |      |
|----------------------|-------------------------|-------------------------------|---------------------------------------------------|------|------|------|
|                      |                         |                               | 10                                                | 15   | 20   | 30   |
| Series 1000 Iron     | R80                     | 0                             | 207                                               | 503  | 834  | 1556 |
| Series 1000 Iron     | R80                     | 20                            | 450                                               | 1025 | 1682 | 3326 |
| Series 1000 Iron     | R80                     | 40                            | 681                                               | 1450 | 2258 | 5142 |
| Series 4600 Steel    | R80                     | 0                             | 118                                               | 334  | 576  | 1166 |
| Series 4600 Steel    | R80                     | 20                            | 310                                               | 755  | 1346 | 2768 |
| Series 4600 Steel    | R80                     | 40                            | 599                                               | 1191 | 2211 | 4018 |
| None                 | MH-100                  | 100                           | 436                                               | 1006 | --   | --   |
| None                 | R80                     | 100                           | 1463                                              | 2794 | --   | --   |

- 5        Thus, for example, a minimum green strength of 1000 psi would be obtained with an 80% atomized 1000 iron /20% R80 metallurgical powder mix at about 15 tsi. (Series 1000 iron is essentially 100 weight percent iron with trace impurities.) If Series 4600 NiMo steel powder were substituted for Series 1000 iron powder in the 80/20 mix, 1000 psi green strength would be reached at
- 10      approximately 18 tsi. If the weight percentage of sponge iron in the Series 4600 steel/R80 sponge iron mix was increased to 40%, 1000 psi green strength could be achieved at approximately 13 tsi. The present invention ideally would mold green compacts at the lowest pressure that provides a part that can be handled without damage. The inventor selected a green strength of 1000 psi minimum as
- 15      being a suitable green strength, although it may be possible to go lower with

certain part shapes without the risk of part damage on handling. If a metallurgical powder is molded at too low a pressure, it will be too weak to handle. If the powder is molded at pressures above the suitable minimum pressure for good green strength, this will detrimentally affect tool life. The 5 results in Tables 1, 3, and 5 indicate that any number of powder blends can be compacted at 20 tsi or less to provide good green strength.

It is to be understood that the present description illustrates those aspects of the invention relevant to a clear understanding of the invention.

Certain aspects of the invention that would be apparent to those of ordinary skill 10 in the art and that, therefore, would not facilitate a better understanding of the invention have not been presented in order to simplify the present description. Although the present invention has been described in connection with certain embodiments, those of ordinary skill in the art will, upon considering the foregoing description, recognize that many modifications and variations of the 15 invention may be employed. It is intended that all such variations and modifications of the inventions are covered by the foregoing description and following claims.